Mini Sprites and Mini Blue Jets in Nanosecond Diffuse Discharge in High-Pressure Nitrogen

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Abstract

In experiment the glow of plasma of nanosecond diffuse discharge in an inhomogeneous electric field was investigated. The glowing formations similar to sprites and blue jets observed during the discharges in the upper layers of atmosphere, were registered under the nitrogen pressure up to 0.7 MPa. It was established that mini jets red colored (mini sprites) appear near plane electrode where electric field is low, and mini jets blue colored (mini blue jets) appear near electrode with a small radius of curvature, where electric field is amplified. When both electrodes have small radius of curvature, only mini blue jets are appeared. Also, the mini sprite was registered in the center of discharge gap near a spark channel. It was shown, that intensity of mini sprites and mini blue jets is increased at increasing pressure of nitrogen up to 0.4 MPa, but subsequent increasing of pressure up to 0.7 MPa leads to decrease of intensity.

Keywords

Mini Sprites; Mini Blue Jets; Runaway Electrons; Runaway Electron Preonized Diffuse Discharge (REP DD); High Pressure; Supershort Avalanche Electron Beam (SAEB)

Introduction

Discharges, the same lightning in the Earth's atmosphere, are investigating by many scientists (see Lyons *et al.*, 2003; Barry *et al.*, 1984; Bazelyan *et al.*, 2001; Ebert & Sentman, 2008; Williams, 2006, and references in these publications). Last years there has been considerable progress in the study of pulsed discharges that occur in the upper layers of the Earth's atmosphere. In the upper atmosphere the radiation of lightning, which has red and blue colors, was registered (Lyons *et al.,*, 2003; Raizer *et al.*, 2010; Gordillo-Vázquez *et al.*, 2011; Pasko, 2007; Pasko *et al.*, 2013; Williams, 2006). At altitudes above 50 km in the red range of the spectrum mainly emit discharges, which are called the sprite (sprites) and halo (halos). Sprites at altitudes of 50-70 km have a form similar large diffuse streamer, and at altitudes of 70-90 km they have a form of diffuse cloud. The halos appear at altitude of 75-85 km and have a form of circle with radius up to 100 km. In the blue range of spectrum at altitudes up to 50 km emit discharges, which are called the blue jets. Such discharges are observed when ordinary lightning "cloud-earth" is occurred. Spectral studies have shown that red color of radiation of sprites is given mainly by nitrogen first positive system, and for blue jets by nitrogen second positive and first negative systems. Physics of lightning are investigated in laboratory discharges. (Bazelyan *et al.*, 2001; Ebert *et al.*, 2006; Ebert & Sentman, 2008; Pasko, 2007; Parra-Rojas *et al.*, 2013; Shao *et al.*, 2011; Beloplotov *et al.*, 2014a; Rahman *et al.*, 2008; Egorov *et al.*, 2004; Hayashi *et al.*, 2008). For example, in papers of Bazelyan *et al.* 2001 and Rahman *et al.* 2008 lightning "cloud – water surface" was simulated, and in papers of Egorov *et al.* 2004 and Hayashi *et al.* 2008 ball lightning was investigated. It should be said, that main attention is paid to ordinary lightning and ball lightning, which occur in lower layers of atmosphere.

In paper of Tarasenko *et al.* 2014 was reported about observation of mini sprites and mini blue jets in a plasma of Runaway Electron Preonized Diffuse Discharge REP DD under the high pressure of nitrogen and air.

Objectives of this work are to show experimental possibility for observing of miniature sprites and blue jets in plasma of a pulse discharge initiated by runaway electron beam under the high pressure of nitrogen (up to 0.7 MPa) and to study influence of electrode geometry on appearance of mini sprites and

mini blue jets.

Experimental Setup and Measurement

Experiments were carried out on setup which was used early to study properties of REP DD (Baksht *et al.*, 2009; Beloplotov *et al.*, 2014a; Beloplotov *et al.*, 2014b; Tarasenko *et al.*, 2014) and SAEB (Tarasenko *et al.*, 2003; Tarasenko *et al.*, 2008; Tarasenko *et al.*, 2011). Detailed description of setup you can find in paper of Beloplotov *et al.* 2014b. Setup consisted of RADAN-220 pulser and discharge chamber filled with nitrogen or air. The pressure of nitrogen ranged from 0.013 to 0.7 MPa. The voltage pulse formed by the RADAN-220 pulser applied through a short transmission line to an electrode with small radius of curvature. In one case, the potential electrode was made of razorblades of thickness of 100 μm and has a length of 19 mm. Grounded electrode was a plane located at a distance of 13 mm from the edge of potential electrode. In the other case, both the potential and grounded electrodes were made of razorblades of thickness of 100 μm and have a length of 19 and 38 mm, respectively. Gap distance was the same. The amplitude of voltage pulses was measured with a capacitive divider located at the end of the transmission line. The voltage pulse duration at a matched load is ~2 ns, and the pulse rise time in the transmission line is ~0.5 ns. The current through the gap was measured with a shunt made of thin-film chip-resistors. For the registration of SAEB current the anode made of a metal grid with transparency 14 % and AlMg foil diameter of 1 cm and thickness of 50 μm was used. SAEB current was measured with a collector simultaneously with the discharge current and voltage pulse in the gap at the negative polarity of the voltage pulse. The collector was located downstream of the anode foil. The radiation from the discharge plasma was registered with photodiode PD025 (cathode is LNS20, Photek company. The pulse rise time is ~80 ps). The glow of discharge plasma was photographed with a digital camera Sony A100. Electrical signals from the capacitive voltage divider, shunt, collector, and photodiode were recorded with Tektronix DPO70604 digital oscilloscope (6 GHz, 25 GS/s). The detectors were connected to the oscilloscope via RadioLab 5D-FB PEEG coaxial pulse cables with standard N-type connectors and Barth Electronics 142-NM attenuators with a bandwidth up to 30 GHz. The integral emission spectra were recorded with a spectrometer EPP-2000C (Stellar-Net Inc.). Experiments were carried out in the single pulse mode at both polarities of the RADAN-220 pulser.

Experimental Results

In Fig. 1 typical waveforms of pulses recorded in nitrogen at pressure of 0.25 MPa are shown. The discharge current pulse duration is more than 30 ns. Discharge current amplitude does not exceed few tens of amps after 30 ns. SAEB is generated at the front of discharge current pulse and at maximal value of amplitude of the voltage pulse. Maximum of radiation intensity is somewhat delayed with respect to the maximum of power of input energy.

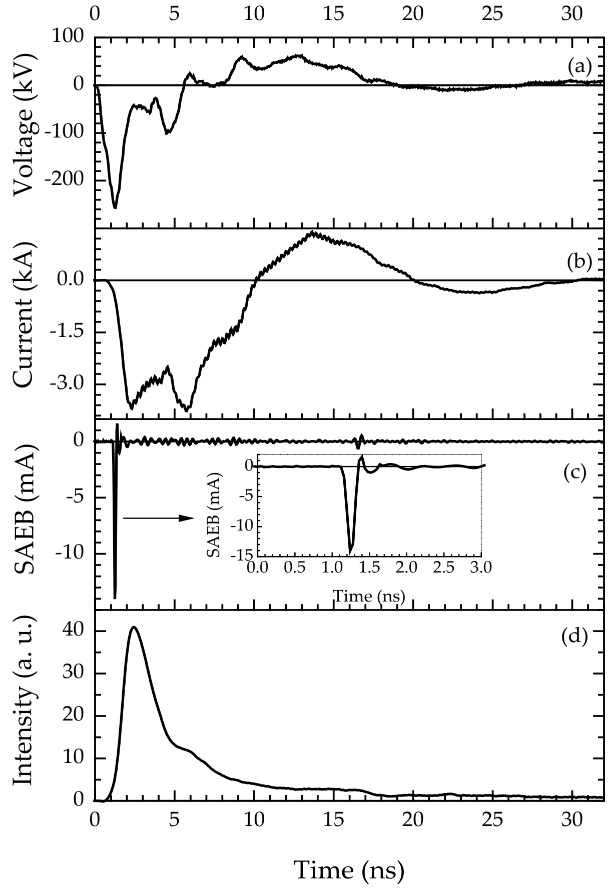

FIG. 1 WAVEFORMS OF VOLTAGE PULSE (A), CURRENT THROUGH THE GAP (B), SAEB CURRENT (C), INTENSITY OF DISCHARGE PLASMA RADIATION (D). NITROGEN PRESSURE IS 0.25 MPA.

Images of discharge glowing for "blade-blade" and "blade-plane" configurations of electrodes are shown in Fig. 2 – Fig. 7 at different pressures of nitrogen and at both polarities. As is well known (see Tarasenko *et al.*, 2008; Levko *et al.*, 2012 and Fig. 1c), runaway electron beams (RAE) and X-rays are registered at nanosecond discharges in gases at elevated pressure. RAE and X-rays make it possible to form REP DD at both polarities without additional preonization source (Kostyrya *et al.*, 2004). Increasing of the pressure or

reduction of the interelectrode distance leads to REP DD constriction. Color of glow of the REP DD depends on experimental condition. Visually, glow of REP DD has blue color in nitrogen at pressure of 0.1 MPa. It is observed on REP DD image. The color of glow of the REP DD can take a reddish tinge at decreasing pressure. Spectral investigations have shown, that the main contribution to radiation is given by the nitrogen second positive system.

Feature of this work is registration of diffuse cloud or diffuse jets near electrodes, which have red and blue color. They have maximum brightness at RED DD constriction. Locations of these diffuse jets change randomly along the electrode. Detailed study of the images under different conditions has allowed to reveal the following characteristics of the radiation of REP DD constriction which had not previously been observed or have not been described in the literature known to us. Only in paper of Tarasenko *et al.* 2014 we presented first preliminary data about observation of such jets with red and blue colors in plasma of pulse discharges initiated by runaway electrons. These jets we named mini sprites and mini blue jets by analogy with the sprite and blue jets, which take place in upper layers of the atmosphere (Fig. 2). However, the size of these discharges differ greatly. Sizes of mini sprites and mini blue jets are about some millimeters, while one of sprites and blue jets are about tens and hundreds of kilometers. As noted above, location of mini sprites and mini blue jets change randomly along the electrode, and their number increase with increasing pressure.

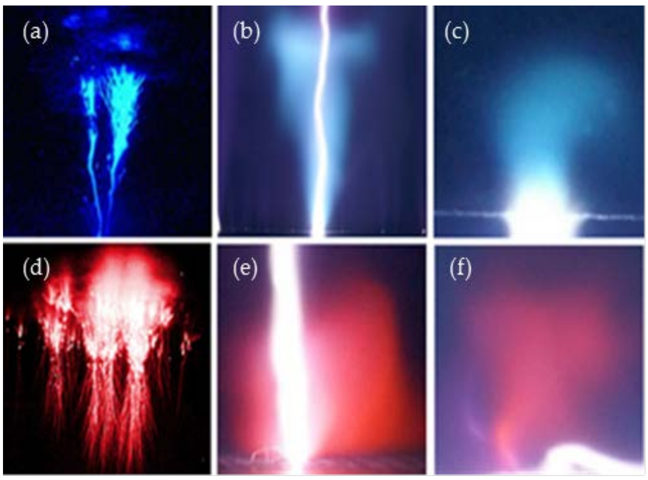

FIG. 2 THE BLUE JET IN THE EARTH'S UPPER ATMOSPHERE (A), THE MINI BLUE JET IN THE DISCHARGE GAP IN NITROGEN AT PRESSURE OF 0.2 MPA (B, C). THE SPRITE IN THE EARTH'S UPPER ATMOSPHERE (D), THE MINI SPRITE IN THE DISCHARGE GAP IN NITROGEN AT PRESSURE OF 0.4 MPA (E, F). SIZE OF MINI SPRITES AND MINI BLUE JETS ABOUT 1-6 MM.

Let us analyze conditions of discharge under which mini sprites and mini blue jets are observed. In Fig. 3 – Fig. 7 the potential blade electrode located at the top of images. In Fig. 3 images of REP DD in nitrogen at pressure of 0.013 MPa are presented. Mini blue jets are observed only near electrode with small radius of curvature. Mini sprites are observed only near plane electrode. The polarity of the voltage pulses had no influence on appearance of one. Hence, to form mini blue jets high electric field is necessary. As well as, mini sprites and mini blue jets appeared near an electrode bright spots.

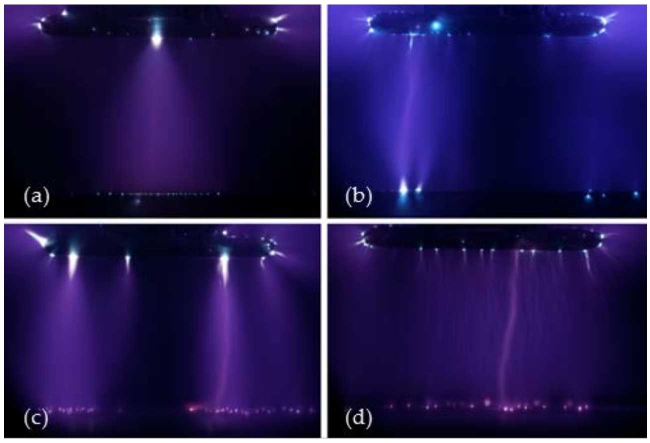

FIG. 3 IMAGES OF DISCHARGE PLASMA GLOW IN NITROGEN AT PRESSURE OF 0.013 MPA. “BLADE-BLADE” (A, B) AND “BLADE-PLANE” (C, D) ELECTRODES CONFIGURATION. NEGATIVE (A, C) AND POSITIVE (B, D) POLARITY.

In Fig. 4 images of REP DD in nitrogen at pressure of 0.1 MPa are presented. In these conditions REP DD is more homogeneous. Mini sprites and mini blue jets have low intensity or are not observed, but intensity and size of them are increased sharply when REP DD constricted (Fig. 4).

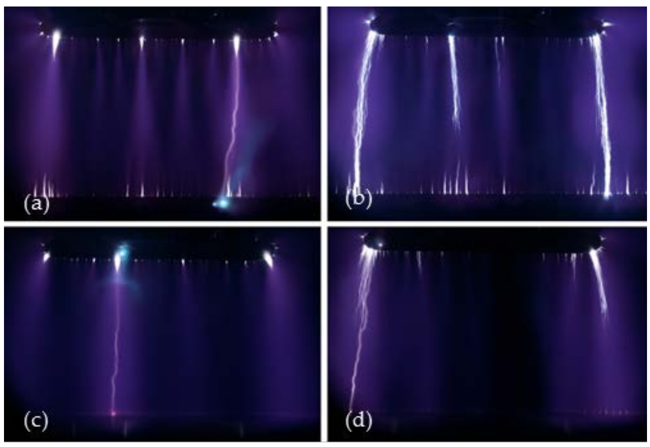

FIG. 4 IMAGES OF DISCHARGE PLASMA GLOW IN NITROGEN AT PRESSURE OF 0.1 MPA. “BLADE-BLADE” (A, B) AND “BLADE-PLANE” (C, D) ELECTRODES CONFIGURATION. NEGATIVE (A, C) AND POSITIVE (B, D) POLARITY.

In Fig. 5 images of REP DD in nitrogen at pressure of

0.2 MPa are presented. As above, mini blue jets locate only near electrode with small radius of curvature, and mini sprites located only near plane electrode. However, in these conditions, for appearance of mini sprites and mini blue jets a spark discharge is necessary (Fig. 4a, b, d). There are only REP DD and electrode bright spots in Fig. 5c.

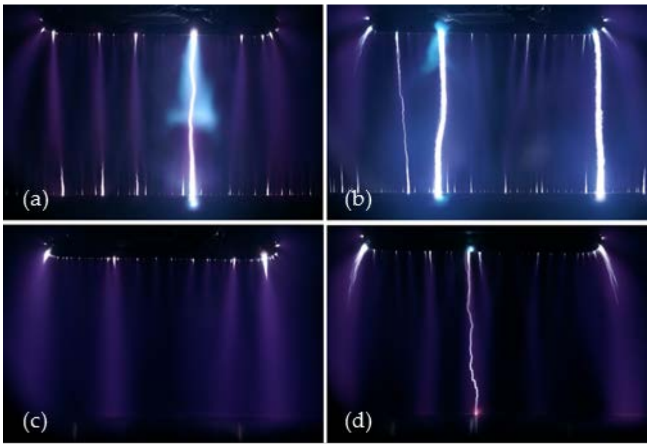

FIG. 5 IMAGES OF DISCHARGE PLASMA GLOW IN NITROGEN AT PRESSURE OF 0.2 MPA. "BLADE-BLADE" (A, B) AND "BLADE-PLANE" (C, D) ELECTRODES CONFIGURATION. NEGATIVE (A, C) AND POSITIVE (B, D) POLARITY.

Under nitrogen pressure of 0.4 MPa the spark discharge became more intense (Fig. 6). These conditions are optimal for mini sprites and mini blue jets. Their intensity and size achieve maximum. In Fig. 6d it is seen, that mini sprite can form in center of discharge gap near spark channel.

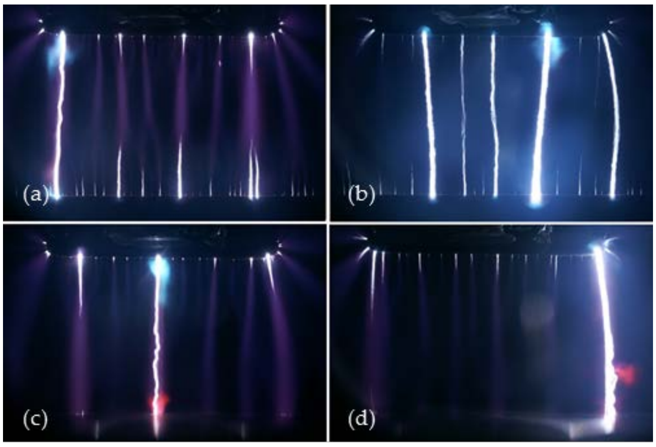

FIG. 6 IMAGES OF DISCHARGE PLASMA GLOW IN NITROGEN AT PRESSURE OF 0.4 MPA. "BLADE-BLADE" (A, B) AND "BLADE-PLANE" (C, D) ELECTRODES CONFIGURATION. NEGATIVE (A, C) AND POSITIVE (B, D) POLARITY.

Increasing pressure of nitrogen up to 0.7 MPa leads to a hard (strong) REP DD constriction. Intensity of spark channels increases. However, mini sprites and mini blue jets are observed on the background of bright spark channels (Fig. 7)

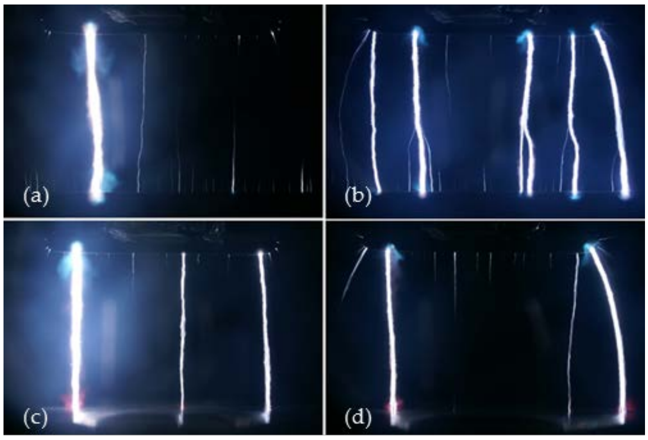

FIG. 7 IMAGES OF DISCHARGE PLASMA GLOW IN NITROGEN AT PRESSURE OF 0.7 MPA. "BLADE-BLADE" (A, B) AND "BLADE-PLANE" (C, D) ELECTRODES CONFIGURATION. NEGATIVE (A, C) AND POSITIVE (B, D) POLARITY.

Waveforms of voltage pulses and current through the gap at both polarities of RADAN-220 pulses for "blade-blade" and "blade-plane" electrodes configuration are shown in Fig. 8. Waveform look alike in the first 10 ns. At this time, about 90% of energy is deposited in plasma.

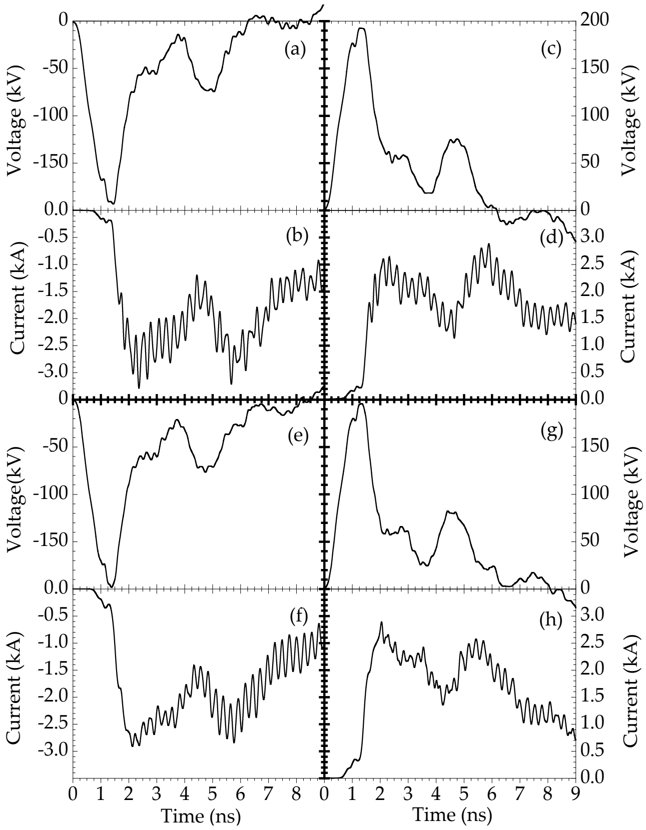

FIG. 8 WAVEFORMS OF VOLTAGE PULSES (A, C, E, G), CURRENT THROUGH THE GAP (B, D, F, H). NITROGEN PRESSURE IS 0.4 MPA. "BLADE-BLADE" (A, B, C, D) AND "BLADE-PLANE" (E, F, G, H) ELECTRODES CONFIGURATION.

We suppose that at least mini sprites appear later. Waveforms and spectra of mini sprites and mini blue

jets wer not obtained, because their location changed randomly and their radiation intensity was less than REP DD plasma radiation intensity. Further study will be focused on obtaining these data. It can be assumed that nitrogen first positive system give a contribution in the radiation of mini sprites, and nitrogen second positive and first negative systems give a contribution in the radiation of mini blue jets, as it takes place in the radiation of sprites and blue jets in upper atmosphere. Presumably, mini blue jets is formed by avalanche of fast electrons formed in electric field amplified near electrode with a small radius of curvature, and mini sprites due to discharge in a low electric field near plane electrode after the main pulse voltage. Moreover, it should take into account that an evaporation of the electrode material can affect the color of radiation near electrodes (Baksht et al., 2012; Rybka D. V. et al., 2013).

Conclusions

The studies allowed to register the glow of diffuse formations in the discharge gap similar to sprites and blue jets observed in the upper layers of Earth's atmosphere. This confirms the complexity of processes at nanosecond breakdown of discharge gaps, when SAEB is generated, that must be considered when using the REP DD, particularly for cleaning and modification of metal surfaces (Baksht *et al.*, 2009; Voitsekhovskii *et al.*, 2012).

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